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INTERACTION OF PLASMA OSCILLATIONS WITH CONDUCTION IN A PENNING GAUGE

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ABSTRACT

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We have observed oscillations at VHF in a Penning Gauge operating at pressures of the order of one micron of mercury in magnetic fields of about 200 Cersteds. The oscillations occur only for certain values of the anode voltage, and concurrent with the oscillations anomalies are observed in the current vs. voltage characteristic of the gauge. This behavior clearly indicates an interaction between these oscillations and the conduction mechanisms in the gauge. An interpretation of the nature of the oscillations and a discussion of their excitation is presented. The details of the interaction are not yet fully understood.

AUTHOR

I. INTRODUCTICN

We shall describe first the experimental observations of VHF oscillations (Crownfield and Dennis, 1962) in a Penning Gauge, and shall then proceed to a discussion of their interpretation in terms of the coupled modes of oscillation for an electron gas enclosed in a conducting cylinder, and to the discussion of the observed behavior of the gauge current as a function of voltage. Finally, we discuss the relation of our observations to those of other observers.

II. THE EXPERIMENTS

Our experiments used a Penning Gauge of the sort shown in figure 1, with a cathode consisting of a brass or aluminum cylinder closed at both ends, which also serves as a vacuum envelope. The anode is a ring of copper wire. A magnetic field is provided parallel to the axis of the cylinder by a large electromagnet. The measuring equipment is shown in the block diagram of figure 2. Cscillations in the anode voltage of the gauge were observed using a radio receiver and a Panadaptor as a spectrum analyser.

The oscillations, as observed on the Panadaptor were frequently observed to have very sharply defined frequencies (within the resolution capability of the instruments), although under some conditions broad-band signals were observed.

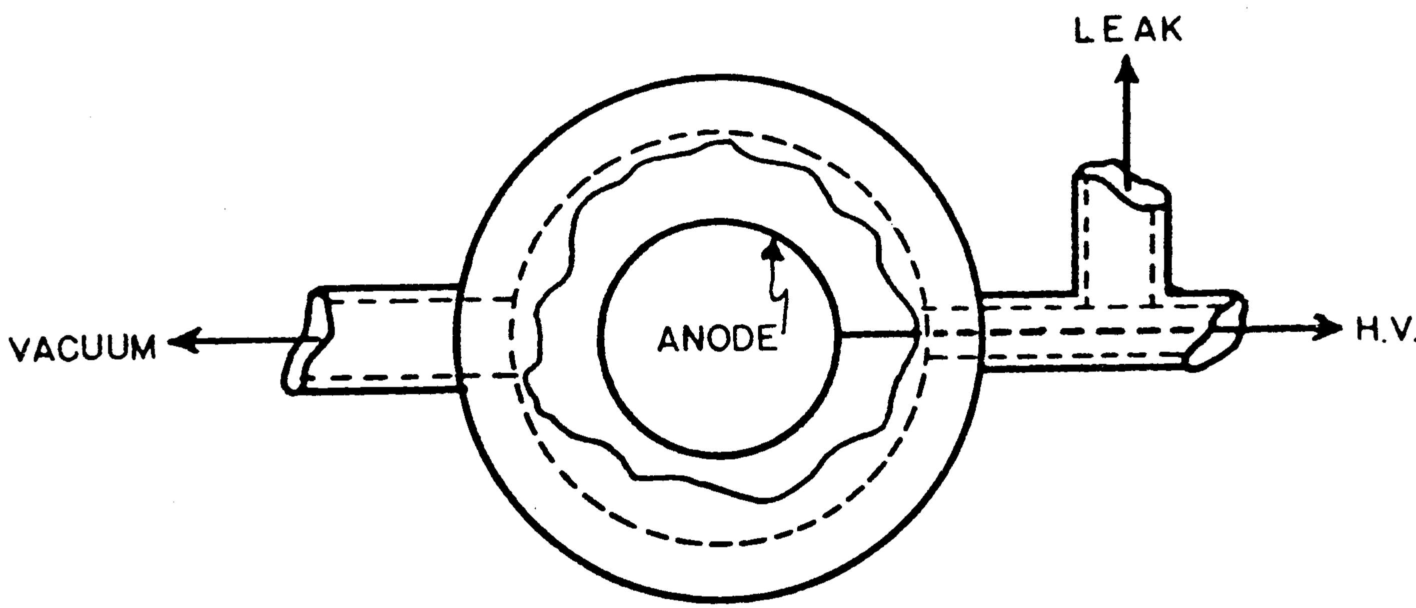

Figure 1. Diagram of the Penning Gauge.

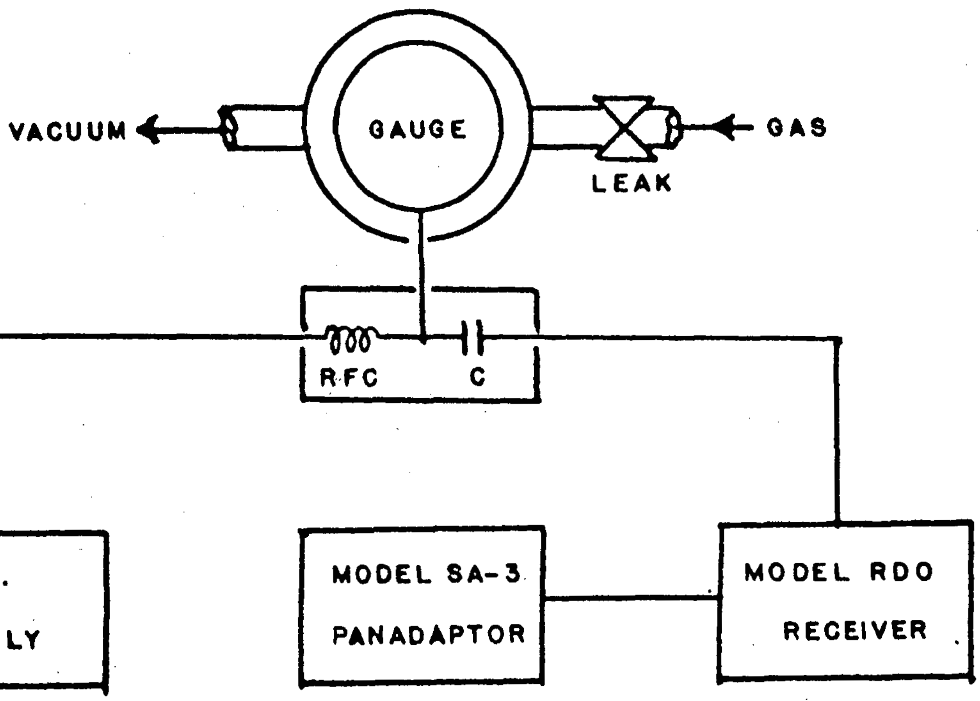

Figure 2. Block diagram of measuring apparatus.

The conditions under which a transition occurs from one kind of oscillation to the other remain to be investigated in a systematic fashion; the present discussion will be limited to the properties of the sharply defined oscillations and their interpretation. Although such oscillations have been observed before (Dumas, 1955), it was rather surprising to us to see how sharp the frequency of such an oscillation could be; in some cases the width could not be distinguished from that of a crystal oscillator signal.

Experiments were done by searching for oscillations within the tuning range of the receiver (approximately 40 to 1000 Mc.), and it was soon noticed that they were only observed concurrent with anomalies in the current vs. voltage characteristic of the gauge. We then proceeded to observe their amplitude and the gauge current concurrently as a function of anode voltage. Qualitative observations were also made of the behavior of the oscillation frequency vs. anode voltage.

Observations of the oscillation frequencies for typical values of magnetic field and at a pressure of about 0.5 micron are shown as experimental points in figure 3. Typical behavior of oscillation amplitude and gauge current as a function of anode voltage are shown in figure 4. The oscillation frequency was observed to increase with anode voltage, and would sometimes jump discontinuously to another frequency. Under some conditions several (two to four) sharply defined oscillations were observed simultaneously.

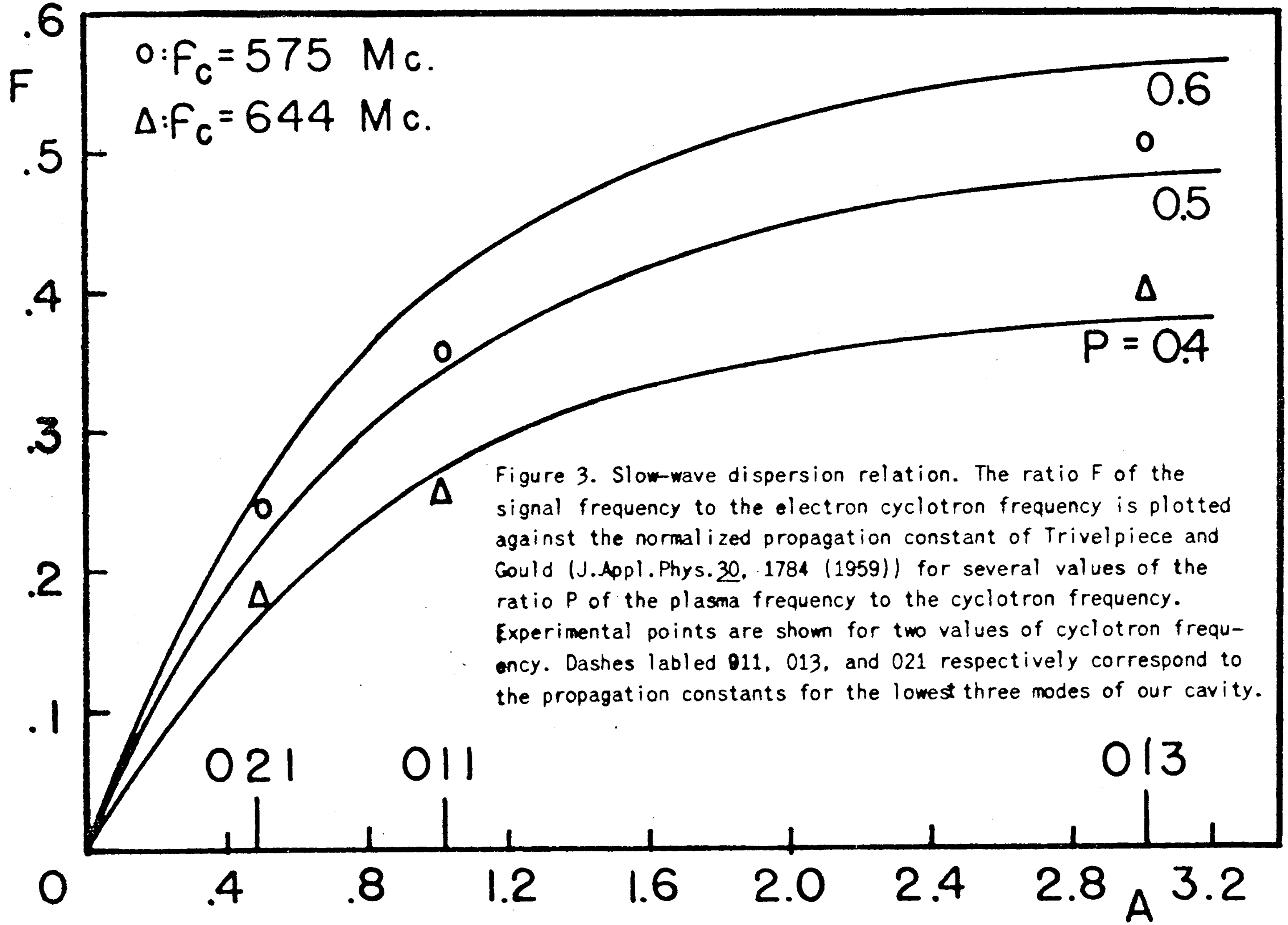

Figure 3. Slow-wave dispersion relation. The ratio F of the signal frequency to the electron cyclotron frequency is plotted against the normalized propagation constant of Trivelpiece and Gould (J.Appl.Phys.30, 1784 (1959)) for several values of the ratio P of the plasma frequency to the cyclotron frequency. Experimental points are shown for two values of cyclotron frequency. Dashes labled 011, 013, and 021 respectively correspond to the propagation constants for the lowest three modes of our cavity.

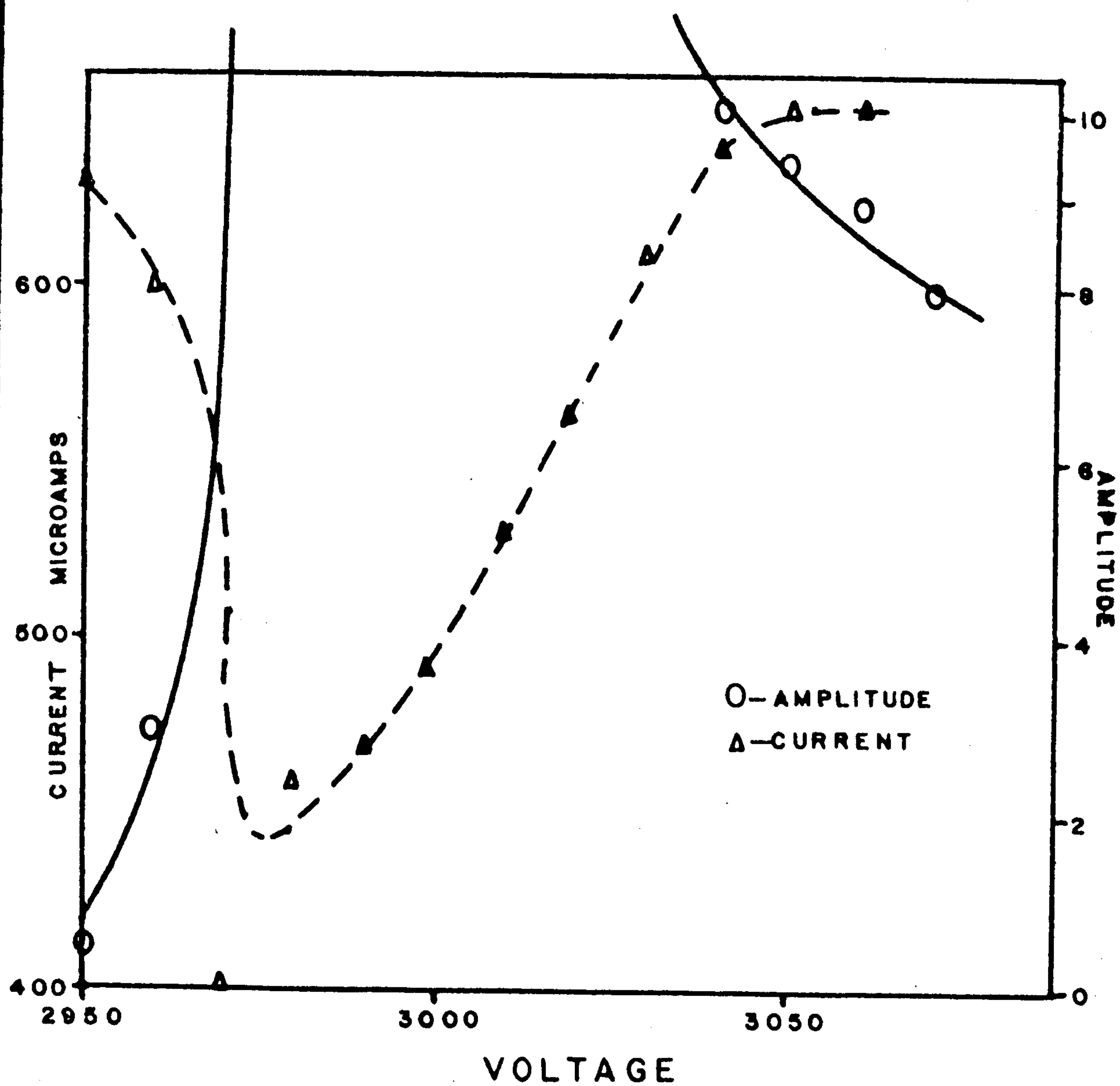

Figure 4. Amplitude of a typical oscillation, and current drawn by the gauge, as functions of the anode voltage.

III. THEORY

For a plasma in a magnetic field, confined in a conducting cylinder, there are several characteristic periodic oscillations possible. If one neglects the coupling of these modes, they may be classified as plasma oscillations, electromagnetic wave modes, cyclotron motion of electrons, and in the case of an externally applied field the electrons may perform oscillations about a potential energy minimum. In an actual plasma, it is not practical to classify these oscillations according to this scheme, because at least some of them are strongly coupled one to another. However, several authors have discussed the possible modes of a plasma-filled conducting cylinder for propagating waves in the presence of an axial magnetic field (Trivelpiece, and Gould, 1959; Bevc and Everhart, 1961). By superposition of waves travelling in opposite directions, these treatments may be modified to obtain the corresponding standing wave modes for a cavity. This automatically takes into consideration all of the oscillations listed above except those corresponding to the oscillation of electrons in a potential well.

Now, if we consider the particular example of the Penning Gauge of figure 1, we find that it provides the possibility of all of the types of oscillations mentioned above. The motion of the electrons parallel to the magnetic field takes place in a potential well due to the presence of the positive anode (Salz, et al, 1961).

We can imagine a mechanism for the coupling of this motion to the other oscillation modes if we note that those electrons moving in one direction, say from left to right, constitute a beam. The coupling may then be envisaged as a beam-plasma interaction. The condition for a large interaction between the beam and the plasma is then that the beam be approximately synchronous with one of the waves in the cylinder. In the cavity system, this is more easily pictured as requiring that the period of the potential well oscillations be nearly the same as that for the plasma oscillations (the latter term is used here to mean oscillations of the first three types mentioned above, since they interact strongly and cannot be classified separately).

The observed properties of the oscillations are easily interpreted in terms of this picture. First, the frequencies of the oscillations fit well to the dispersion relation of Trivelpiece and Gould (Trivelpiece and Gould, 1959). Second, the oscillations occur only for certain values of anode voltage. Finally, the amplitude and frequency dependence of the oscillations agree with those expected for coupled oscillations when one oscillator of the coupled pair is driven and the properties of the other are observed.

The effect of anode voltage on the oscillations will be clearer when the reader is reminded that the anode voltage determines the depth of the potential well, and hence the period of the corresponding oscillations.

The source of the energy which maintains these oscillations is clearly the D.C. power supply used to operate the gauge. It would furthermore seem reasonable that the amplitude of these oscillations would be relatively independent of the anode voltage, so that the amplitude of the plasma oscillations would exhibit a resonance as the anode voltage is varied. The frequency observed would correspond to that of one of the normal modes of the coupled pair of oscillations, and jumping from one mode to the other as well as simultaneous appearance of two frequencies is not surprising. Since the ultimate source of the energy to maintain oscillation is the D.C. power supply, it is to be expected that the occurrence of oscillations would react back on this supply; since a constant voltage supply is used, the only possible result is a change in the current drawn by the gauge. The explanation of the exact behavior of the current must await a quantitative discussion of the mechanism by which conduction takes place in the Penning Gauge.

IV. DISCUSSICN

As may be seen from figure 3, the frequencies observed agree well with the dispersion relation for slow-waves in a plasma-filled conducting cylinder. The points correspond to the wave-numbers of the lowest three modes of the cavity under the following boundary conditions: the cylinder is considered a constant potential (this would not be valid for fast-wave modes), and the anode ring must be an equipotential, but not at constant potential.

The data are seen to be consistent with a Langmuir plasma frequency of about 300 Mc., a not-unreasonable value.

Figure 4 shows the behavior of oscillation amplitude and anode current as a function of applied voltage. The resonance behavior of the amplitude is quite striking, and a pronounced dip in the current occurs. In making these observations, quantitative data were not taken regarding the oscillation frequency as a function of anode voltage, but observation using the Panadaptor showed the behavior to be qualitatively as expected. In some cases, furthermore, mode-jumping and/or simultaneous oscillation at two frequencies was observed. In fact, sometimes more than two frequencies were observed, and variation of the magnetic field and/or pressure sometimes resulted in broad-band oscillations over several megacycles in bandwidth. Further experiments are planned in order to determine the characteristics of the transition from well-defined frequencies to broad bands of oscillations.

We believe that the oscillation in a Penning Gauge observed by Dumas (Dumas, 1955) were of the same nature as those discussed here; however, the spectrum of our oscillations does not agree with that observed by Knauer, et al. (Knauer, 1961). This is not too surprising because the geometry of the gauge used in those experiments is different from ours. This possibility receives further support from observations at MIT (Cooke and Hartmen, 1962).

In the latter experiments, anomalies were observed in the volt-ampere characteristic for gauges whose geometry resembled ours, but not when the geometry resembled that of Knauer. Finally, we would like to emphasise that our Penning Gauge operates in an entirely different region of the volt-ampere characteristic than many of the PIG experiments currently underway, and the oscillations observed are quite different from those observed, for example, by Landauer (Landauer, 1962).

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